

HIGH β STUDIES IN CURRENT RAMP DOWN SCENARIOS IN TOKAMAK TUMAN-3M

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1. Introduction

In this paper the results of experimental study of a possibility to increase β_T and β_N in a circular cross-section tokamak without auxiliary heating are presented. The experiments were performed in the TUMAN-3M tokamak [1]. The device has following parameters: $R_0=0.53$ m, $a_l=0.22$ m (circular limiter configuration), $B_T \leq 1.2$ T, $I_p \leq 175$ kA, $\bar{n}_e \leq 6.2 \cdot 10^{19} \text{ m}^{-3}$. Stored energy was measured using diamagnetic loops and compared with calculated from kinetic data obtained by Thomson scattering and microwave interferometry. Measurements of the stored energy and of the β were performed in ordinary Ohmic regime, in Ohmic H-mode [2] and in

the scenario with fast Current Ramp-Down in Ohmic H-mode. The β values in boronized vessel [3] were compared with that ones obtained before boronization.

To increase β_T in Ohmic H-mode, the intensive gas puffing was used. Diamagnetic data obtained in Ohmic H-mode before and after boronization are collected on the diagram displaying β_T as a function of parameter I/aB - fig.1. Here open triangles correspond to the shots produced before and filled ones to the shots after boronization. Data shown on the diagram indicate substantial increase in the β_T as a result of boronization [4]. At similar I/aB maximum toroidal beta is by a factor of 1.5 higher in boronized vessel compared to unboronized. Highest achieved β_T was 2.0 % at $n_e=6 \cdot 10^{19} \text{ m}^{-3}$. Corresponding value of β_N

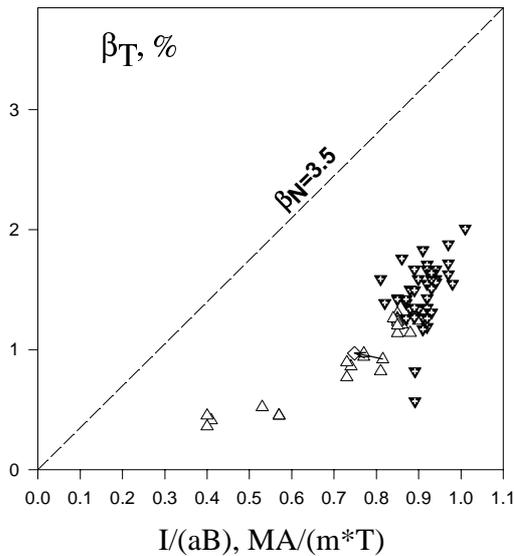


Fig. 1. β_T as a function of parameter $I/(aB)$ before and after boronization in TUMAN-3M.

was 2. This is far from Troyon limit 3.5 but exceeds β_N achieved in other tokamaks in OH regime [5,6]. Further increase of the energy content was impossible because of confinement degradation, which reveals itself as saturation of β_T appearing before density saturation and as saturation of density despite of continuous gas puffing.

2. Current ramp-down experiment

To increase β_N , plasma current was ramped down after the Ohmic H-mode establishing. It could not enhance energy content of the plasma, but should have led to increase in normalized

β and might have given an opportunity to approach the MHD limit.

Current Ramp Down (CRD) was performed by applying a negative voltage to the transformer primary. It resulted in plasma current decay with a rate of approx. 25 MA/s. Plasma equilibrium along the major radius was controlled by a feedback circuit. Waveforms of the loop voltage, plasma current, D_α radiation and averaged density in a shot with CRD in Ohmic H-mode are shown on fig.2. Gas puffing rate didn't change during the CRD. In spite of this, plasma density started to decay immediately after the CRD was switched on. The stored energy decrease rate caused by CRD was slightly less than density's. This allows to obtain some increase in β_N . Figure 3 displays temporal voltage, stored energy, β_T and β_N in expanded

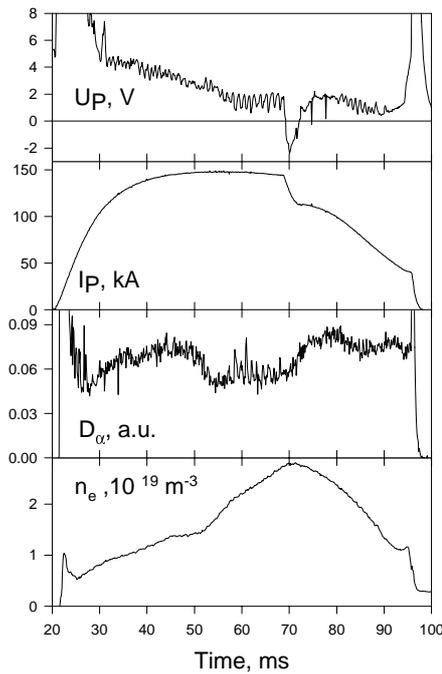


Fig. 2. Temporal evolution of some plasma parameters in the shot with fast Current Ramp-Down.

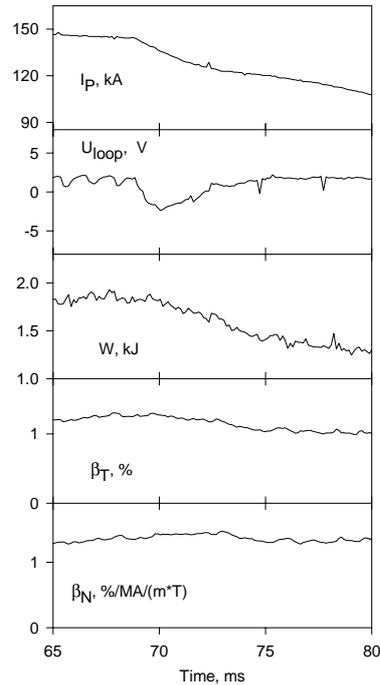


Fig. 3. Behavior of the plasma current, loop voltage stored energy, β_T and β_N in the CRD.

time window. It is seen that during first 2-3 ms after CRD turning on β_N increases slightly. This result is marked on fig.1 by an arrow originating from triangle corresponding to Ohmic H-mode and directed to diamond displaying CRD.

No enhancement of MHD activity was observed in CRD regime. The impossibility to increase significantly β_N was determined by a degradation of the confinement caused by CRD. On the other hand, plasma behavior after the CRD clearly indicated termination of the Ohmic H-mode as a result of sharp current decrease (density increase changes to decay, and D_α returns to its L-mode level, see fig.2).

Time delay between CRD switching on and H-L transition was less than 1 ms. This value is small as compared to the energy confinement timescale. This delay didn't depend noticeably on the value of current step down. Moreover, it was found impossible to prevent from H-L transition caused by CRD using an auxiliary ICR heating, as we plan earlier [4].

These facts do not confirm our preliminary hypothesis of Ohmic H-mode termination by thermal balance breaking resulting from CRD.

3. Effect of time dependent plasma current on a radial electric field

It is well known that radial electric field plays a key role in H-mode behavior [7]. Externally applied radial electric field of both signs can trigger H-mode transition, whereas in a spontaneous Ohmic H-mode plasma \mathbf{E}_r is negative, i.e. directed inwards [8]. The radial electric field evolution in H-mode was described in [9] in a frame of revised neoclassical theory. We suppose that an additional mechanism may play a role in \mathbf{E}_r generation and H-L and L-H transitions in TUMAN-3M plasma. This mechanism employs a fact that in Ohmic Heating regimes in TUMAN-3M electrons and ions at the plasma periphery are in different

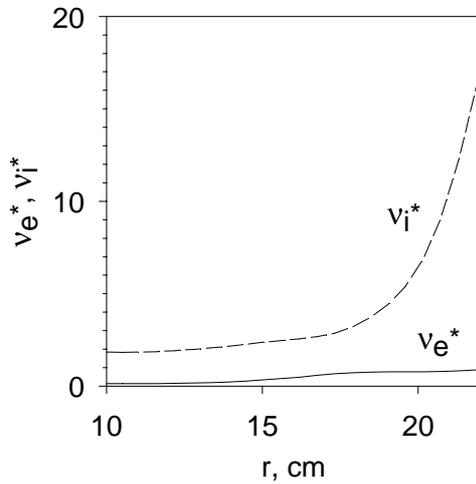


Fig. 4. Ion and electron collisionality in Ohmic H-mode in TUMAN-3M

regimes of collisionality: $v_e^* < 1 < v_i^*$, i.e. ions are in “plateau”, whereas electrons are in “banana” regime, see fig.4. This difference originates from relatively low ion temperature in Ohmic regimes of TUMAN-3M: typically for $r/a \approx 0.8$ T_i is of the order 40 eV, whereas electron temperature can be as high as 120 eV. Hence, the Ware drift is much stronger for electrons than for ions in Ohmic H-mode in TUMAN-3M, leading to excitation of radial current directed outwards (or, in other words, negative charge accumulates in a central region of the plasma column). In a steady state no radial current is allowed in a tokamak, and the effect reveals itself as radial electric field generation and poloidal rotation spin up. This effect, together with a mechanism

proposed in [9] might be responsible for the negative sign of \mathbf{E}_r in Ohmic H-mode.

In CRD experiment, toroidal electric field \mathbf{E}_ϕ at the plasma edge changes its sign, so does the Ware drift velocity (which is proportional to $\mathbf{E}_\phi \times \mathbf{B}_\phi$). This is followed by a transient radial current excitation, which destroys negative Ohmic H-mode \mathbf{E}_r . As a result, “natural” Ohmic H-mode radial electric field diminishes, and H-mode terminates. In a sense, this situation is similar to the experiment on TUMAN-3 Ohmic H-mode termination by a positive biasing applied to the plasma edge by an external electrode [8]. In addition, in time dependent toroidal electric field $\mathbf{E}_\phi \neq \text{const}(t)$, a correction to the Ware drift arises [10]. This may enhance the radial electric field decay even more.

Characteristic time of these processes is determined by a poloidal rotation relaxation, which is governed by neoclassical longitudinal viscosity [9] and is of the order $v_i^{-1} \leq 1\text{ms}$ for TUMAN-3M plasma parameters. This explains very short time delay between CRD switching on and Ohmic H-mode termination.

In the frame of the model proposed above, ICR heating might help to reestablish the ambipolarity of Ware drift at the plasma periphery. Effective ion heating of target Ohmic H-mode TUMAN-3M plasma could lead to decrease in ion collisionality, and when V_i^* is less than 1 ("banana" regime) the Ware drift will be important for ions as well. This should lead to a compensation of negative charge loss caused by CRD, and prevent from decay of negative radial electric field. The failure to use ICRH together with CRD to sustain the H-mode might be a result of low heating power level utilized in the recent experiments on TUMAN-3M.

4. Conclusions

The experiments have shown that maximum values of $\beta_T \approx 2.0\%$ and $\beta_N \approx 2.0$ can be achieved without auxiliary heating. Achieved β_N limit reveals itself as "soft" (non-disruptive) limit. Stored energy saturates during density rise or slowly decays after Current Ramp-Down. Possible explanation for β_T and β_N restrictions is enhanced transport near density limit, or (in the case of CRD) a result of H-L transition. A mechanism of radial electric field formation based on non-ambipolarity of Ware drift under conditions of different collisionality of electrons ("banana" regime) and ions ("plateau" regime) is suggested for explanation of CRD influence on Ohmic H-mode. The reversal of the Ware drift of electrons in peripheral plasma caused by CRD is thought to be a reason for H-mode termination in this scenario. ICR heating used simultaneously with CRD didn't help to avoid the H-mode termination, possibly due to the lack of the auxiliary heating power.

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